Variable Emissivity Through MEMS Technology

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Abstract. All spacecraft rely on radiative surfaces to dissipate waste heat. These radiators have special coatings that are intended to optimize performance under the expected heat load and thermal sink environment. Typically, such radiators will have a low absorptivity and a high infrared-red emissivity. Given the dynamics of the heat loads and thermal environment it is often a challenge to properly size the radiator. In addition, for the same reasons, it is often necessary to have some means of regulating the heat rejection rate of the radiators in order to achieve proper thermal balance. The concept of using a specialized thermal control coating which can passively or actively adjust its emissivity in response to such load/environmental sink variations is a very attractive solution to these design concerns. Such a system would allow intelligent control of the rate of heat loss from a radiator. Variable emissivity coatings offer an exciting alternative that is uniquely suitable for micro and nano spacecraft applications. This permits adaptive or "smart" thermal control of spacecraft by varying effective emissivity of surfaces in response to either a passive actuator (e.g., a bi-metallic device) or through active control from a small bias voltage signal. In essence the variable emittance surface would be an "electronic louver." It appears possible to develop such "electronic louvers" through at least three different types of technologies: Micro Electro-Mechanical Systems (MEMS) technology, Electrochromic technology and Electrophoretic technology. This paper will concentrate on the first approach using both MEMS and Micromachining technology to demonstrate variable emissivity.

BACKGROUND

All spacecraft and the instruments they support require an effective thermal control mechanism in order to operate as designed and achieve their expected lifetimes. In an increasing number of satellites, optical alignment and calibration require a strict temperature control. Traditionally, the thermal design is part of the spacecraft layout determined by all subsystems and instruments. Heat load levels and their location on the spacecraft, equipment temperature tolerances, available power for heaters, view to space, and other such factors are critical to the design process. Smaller spacecraft with much shorter design cycles and fewer resources such as heater power, volume, and surface, require a new, more active approach.

A number of active methods that vary the heat rejection rate in some controlled fashion are commonly used to maintain a reasonable thermal equilibrium. One such method is to cold bias the spacecraft and use simple electrical resistance make-up heaters to control the temperature. However, this can require considerable electrical power, which the spacecraft may not have available at all times. Another approach is to employ a radiator connected with variable conductive heat pipes**, capillary pumped loops, and/or** loop heat pipes. Typically, this adds significant weight, cost and complexity to the systems **and can, at least for heat pipes,** introduce new issues concerning ground testing. Another approach is to use mechanical louvers that can be opened to expose a radiative surface. While functional, traditional mechanical louvers are bulky, expensive, subject to damage, and require significant thermal analysis to evaluate the effect of different sun angles.

The concept of using a specialized thermal control coating or surface which can passively or actively adjust its emissivity in response to variations in load and environmental conditions is a very attractive solution to these design concerns. Variable emittance thermal control coatings have been under development at NASA-Goddard Space

Flight Center (GSFC) since the mid-1990's. These coatings change the effective infrared-red emissivity of a thermal control surface to allow the radiative heat transfer rate to be modulated upon command. Two technologies have been under consideration, electrochromic and electrophoretic devices. The emittance modulation in electrochromic devices is achieved using crystalline electrochromic materials whose reflectance can be tuned over a broad wavelength (2 to 40 microns) in the infrared. Electrophoretic devices involve the movement of suspended particles through a fluid under the application of a small electrical field. When an electric field is applied the flakes, which are made of a material with high reflectivity, they align themselves and form an essentially flat reflective surface.

Another technique to vary the emissivity of a surface involves the use of mechanical louvers, where a mechanical vane or window is opened and closed to allow an alterable radiative view to space. (Gilmore, 1994). Current micro-machining techniques allow the designer to generate arrays of such structures with feature sizes on the order of micrometers (Helvajian, 1997). The three variable emissivity technologies have been chosen as a demonstration technology on NASA's New Millenium ST5 " Nanosat Constellation Trailblazer" mission. Each technology will control a 20 cm x 6 cm radiator area on one of the three nanosats.

MEMS LOUVERS

Louver Design

Micro-electro-mechanical (MEMS) louvers are similar to miniature venetian blinds that can be opened or closed to expose an underlying high emissivity radiator. The "effective emissivity" of the surface can be modulated in a controlled fashion by varying either the angle of the micro-louvers or the total number of micro-louvers that are opened. Figure 1 shows three different designs for the concept. The simplest design is a single louver, which can be opened through 90 degrees. While a smaller opening angle would allow for more variation, it also requires different control due to the influence of the solar position. In the open position, the louvers will expose the high emissivity substrate material to space. In a second design, multiple levels of sliders move across each other. In this case, the total area which can be exposed depends on the number of layers available in the fabrication process. Advantages of this approach include the two-dimensional design, the linear variability of exposed area, and the sturdiness of the design. A third design looks more like a folding door. This design is more complicated than the other two since it uses more hinges, but we expect it to be more sturdy than the single louvers while providing the same active area. Preliminary experiments have shown that these devices are less likely to break during release and operation.

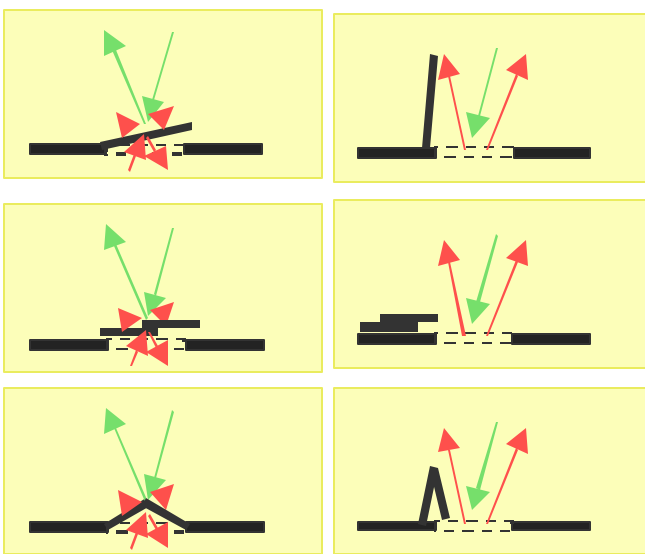

Figure 1: Different concepts for a thermal control louver: Top: Louver ; Middle: Slider; Bottom: Folder

Our early efforts focused on the design of the louvers for fabrication using the MCNC Multi-User MEMS Process (MUMPs). To date, two generations of prototype chips of MEMS louvers have been developed. Both sets were designed at the Applied Physics Laboratory (APL), fabricated at the MCNC Technology Applications Center under the MUMPs program, and subsequently released and tested at APL. The base material for the current devices is polysilicon and the exposed, top surface is coated with gold, which has a very low emissivity of **0.02**.

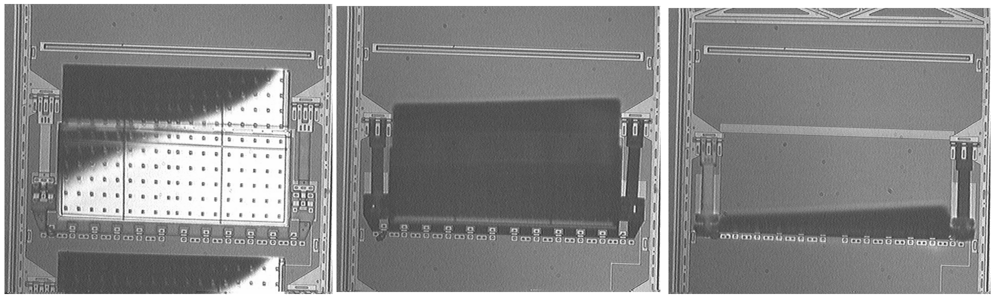

FIGURE 2a: Images from video of MEMS louver opening

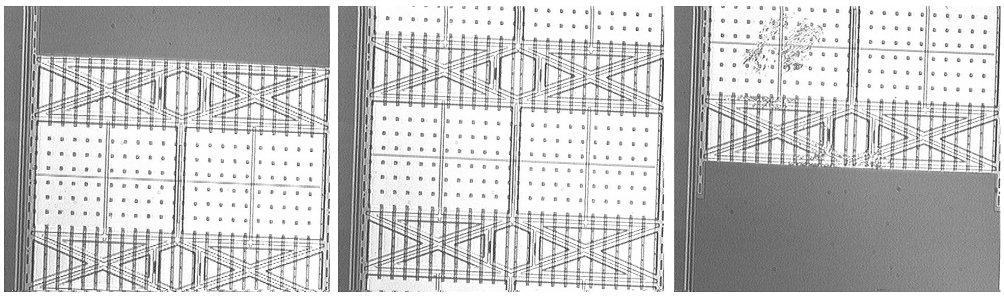

FIGURE 2b: Images from video of MEMS slider opening

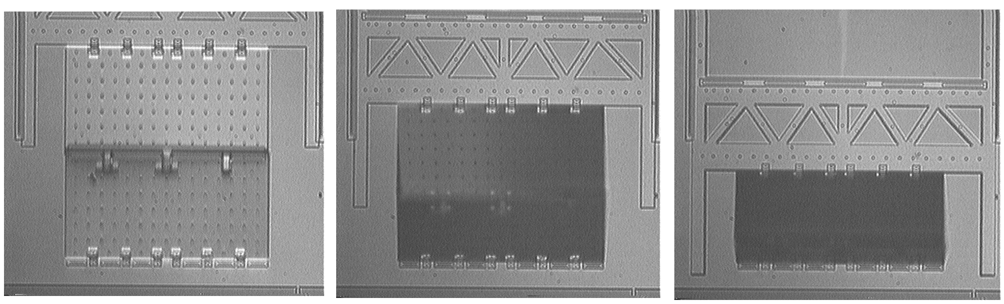

FIGURE 2c: Images from video of MEMS folder opening

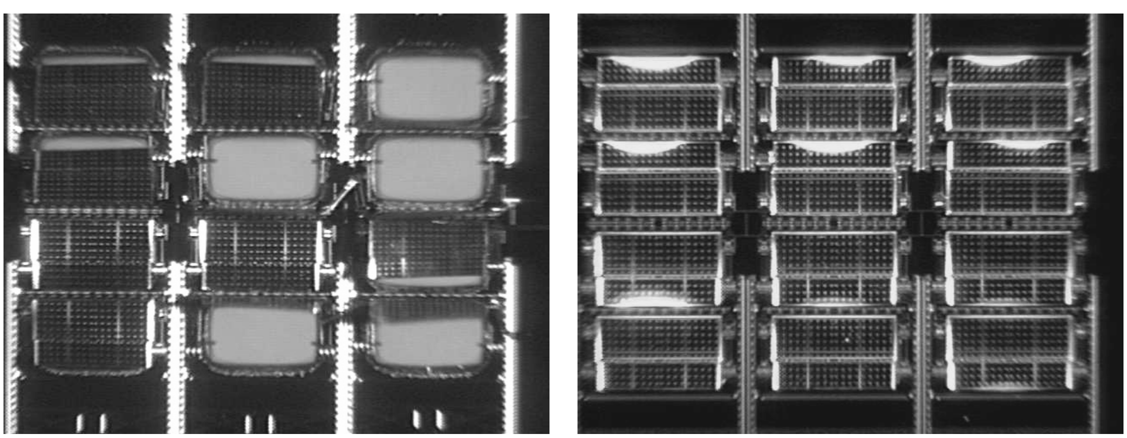

FIGURE 3: Optical Image of a louver array, with **some** louvers **open** (left) and all louvers closed (right). The open louvers expose the background through the etched openings.

Comment on Figure 3; do we have a picture with all louvers open and the emissivity data to go with it?

The coated areas are intended to cover an underlying, high emissivity surface. Images taken from videos of devices in operation are shown in Fig. 2. In the most recent generation, multiple sets of louvers have been grouped together to allow for measurements of emissivity variation using an infrared imager. Further, the silicon substrate under the louvers has been removed using reactive ion etching (RIE) to expose the high-emissivity substrate. **This is desirable since silicon, while generally transparent in the IR, still retains a high reflectivity.** Optical images of a group of louvers is shown in Fig. 3, with some louvers in the open position (left) exposing the bright background.

Infrared Emissivity Measurements

Although the louvers are not mounted on a radiator, infrared images taken at room temperature **(can we address the implications of this?)** in the 8-12 µm wavelength range allow for a reasonable estimate of their performance to be made. Infrared images were taken using a Mikron Scanner, which scans the image with two mirrors onto a HgCdTe detector with a spatial resolution of 320x240 pixels. Using a close-focus attachment, the pixel resolution was on the order of 20 µm per pixel. Calibration was performed on an emissivity standard and the room temperature background was subtracted. An emissivity image of the MEMS louvers is shown in Fig. 4. The structures include multiple sets of louvers on the left, gold-coated "sliders" on the upper right, and the bare SiN layer lower right. All devices are on a Si substrate.

The measured emissivity varies from 0.3 for the SiN to 0 for gold (0.02 is the literature value (Wolfe, 1985)). The same measurements were performed for the louver arrays in the closed and open position. The emissivity images in the area denoted by the dashed line are for an array of louvers that are (a) closed, (b) partially open and (c) fully open. The average emissivity, *e*, for the louver area is 0.18, 0.26, and 0.30, respectively. The emissivity was calculated **(?? Measured??)** according to $e = 0.3 * A_0 + (n - n_c) * A_n$, **{is this equation right? I came up with $e_{measured}$ = (0.3)*(fraction of total area without louvers) + (0.02)*(fraction of area with gold covering that is flat to surface) + ($e_{substrate}$)*(fraction of area with open louvers) }** where A_0 is the uncovered area, n is the number of louvers with area A_n, and n_c is the number of closed louvers. **{Since this is still really a calculated number, is it better to simply say that the effective e is biased by the fraction of the total area that is dedicated to parts other than louvers?}** Future experimental setup improvements will allow measurements to be taken at increased temperatures with reduced background radiation

Based on the measurements, it was found that the variation in effective emissivity of the prototype devices was forty percent. **{I figured out how you got this but it is confusing.}** Note that a sizeable fraction of the area over which this measurement was made (within the dashed lines of Fig. 4) is devoted to mechanical structures supporting the louver operations. Through design modifications, we believe that the ratio of louver area to support structure area can be increased by up to a factor of two. This would increase the variation in effective emissivity to eighty percent.

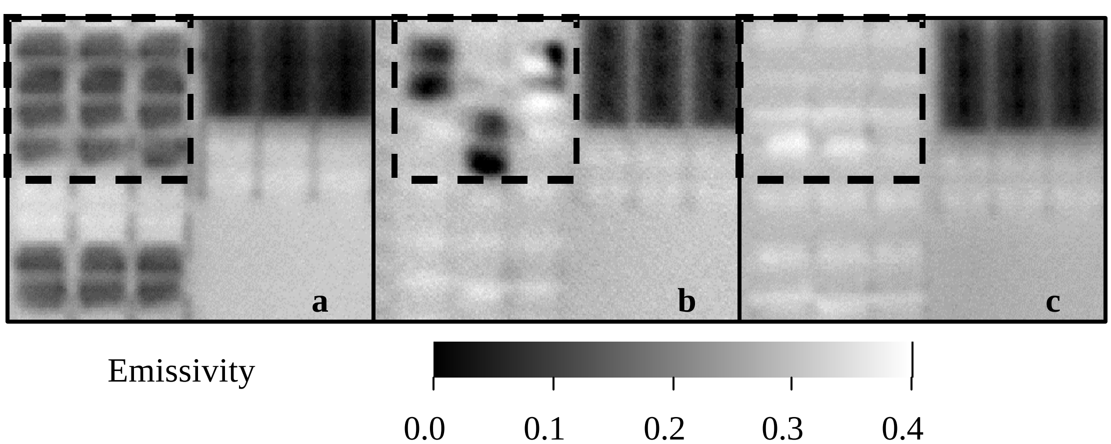

FIGURE 4: Emissivity image of MEMS louvers in various positions. The average emissivity in the region within the dashed lines is 0.18 (a), 0.26 (b), and 0.31 (c). **Can this be updated with our newer data with all louvers open?** Note that the bottom SiN layer has an emissivity of 0.30.

Louver Actuation

For a successful application of the louver concept for spacecraft thermal control, an actuation mechanism has to be identified which allows the highest individual louver control possible with a minimum of space necessary. Note, that all the space covered by the actuation is not active and presents an emissivity bias. Highly individual louver control provides the best accuracy in setting the emissivity and further allows increased control of the spatial emissivity variations **and operational redundancy**. Further, low power consumption and zero power in a static condition are required for small spacecraft applications. Several actuation mechanisms have been considered and in part, implemented. One implementation was the use for an electrostatic comb drive. While this is a low power, reliable and straight-forward designed MEMS actuation mechanism, disadvantages arise due to the large area requirement and, from a space-craft perspective, the relatively high driving voltages (10s V) required. **Build up of static charges on the radiator surface for space environmental effects may also be an issue.** Another mechanism used in some prototype louvers is a “heatuator”(Butler, 1999), which does not have the high voltage requirement and takes up relatively less area on the louver chip. It is possible to locate both types of actuators outside of the active area above the radiator.

Another actuation mechanism under consideration involves coating the actuation structures with a metal other than gold to create a bi-morph that can be heated electrically to generate motion due to different thermal expansion coefficients. Such an actuation mechanism could be used to build a “smart” device where the surface temperature directly controls the louver actuation. Similarly, shape memory alloy coatings such as Nitanol™ could also be used for the actuators (Seguin, 1999).

Reliability Aspects

There are many reliability issues surrounding the extended use of MEMS devices for spacecraft applications (Stark, 1999). The louvers must survive through the launch and operate in the harsh environment of space. In addition, the effects of pre-launch storage must also be taken into consideration. A non-exhaustive list of the of MEMS reliability concerns includes: stiction, wear, fatigue, **contamination,** and radiation effects. An extended evaluation of these issues is currently under study and only a brief overview follows.

Although stiction has not been observed in the prototype devices, the MEMS louvers are probably susceptible to this failure mechanism as a result of electrostatic interactions, capillary forces, or even localized cold welding (Patton, 1999). These concerns can be addressed in several ways. For example, proper ground design should minimize the potential mechanical seizure due to electrostatic clamping. Excessive condensation of moisture, especially during pre-launch storage, can be mitigated through the use of hydrophobic coatings **and outgassing techniques**. Furthermore, appropriate packaging could be employed to prevent the accumulation of water and other contaminants on critical surfaces of the devices.

While relative humidity (RH) levels in excess of 70% have been associated with been degraded mechanical performance attributed to increased stiction, elevated frictional wear between contacting parts has been observed in extremely low RH environments (Tanner, 1999). Due to the low RH of the intended operational environment, the possible degradation of the hinge joints over the device lifetime is an important issue. **Minimum lifetimes will be on the order of 10,000 to 50,000 cycles.**Various coatings and design modifications to minimize friction are being considered. Similarly, the effects of fatigue on hinges and actuators are also being examined.

Finally, in a space environment, the MEMS louvers will be subjected to high energy irradiation. As a result, charge buildup in dielectric layers could occur which may lead to inconsistent or degraded operation of either the louvers or electrostatic actuators. While this obstacle is not insurmountable, it further builds the case for passive louver actuation using “smart” materials.

SUMMARY AND FUTURE DIRECTIONS

To date, two generations of prototype MEMS louvers have been developed which clearly demonstrates the feasibility of using arrays of devices for miniaturized satellite thermal control. Successful actuation of the initial devices and the results of preliminary emissivity testing indicated the validity of the hinged louver concept for thermal control applications. After verification of space qualification of the louvers, the next step will be to fly one or more very small prototypes in a standard calorimeter as experiments on an upcoming spacecraft.

Numerous future NASA missions, such as the ST5 Nanosat Constellation Trailblazer, will undergo significant changes in its thermal environment and will require means of modulation in the spacecraft's heat rejection rate. Specifically, the Trailblazer spacecraft will undergo an approximately 2-hour or longer eclipse during which time the instruments must survive and possibly operate. Given their small capacity for power storage by batteries and low thermal capacitance, the best strategy will be to "close off" their radiator area and radically reduce their heat loss rate. One recent study by Aerospace Corporation[2] predicted heater power savings of 50 to 90% and a nearly 4:1 reduction in component temperature variations. In addition to the obvious weight and power savings, the technology of MEMS louvers for thermal control would greatly simplify spacecraft design and qualification testing and also allow adaptive response to changing power levels or unexpected thermal environments once on-orbit.

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